

Tests of the Standard Model with Low-Energy Neutrino Beams

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We discuss the possibility of using future high-intensity low-energy neutrino beams for precision tests of the Standard Model. In particular we consider the determination of the electroweak mixing angle from elastic and quasi-elastic neutrino-nucleon scattering at a superbeam or β -beam.

1. The High-Intensity Frontier and Neutrino Beams

The search for new physics beyond the standard model in the future will follow two main paths: higher energy and high-intensity [1]. Neutrino facilities will play an important role in this program: neutrino masses take us beyond the standard model, and a full determination of the pattern of ν masses and mixing will require dedicated high-intensity neutrino beams [2]. However, a high-intensity ν beam can be used not only to study neutrino properties, but also as a sensitive probe of the electroweak interaction. Indeed, it has been shown that a wide spectrum of otherwise very difficult or impossible measurements of strong and electroweak processes would become possible at a high-energy neutrino factory [3].

Here we start addressing the issue whether equally interesting measurements might also be possible with a *low energy* but sufficiently intense ν beam. Indeed, the main role so far of low-energy tests of the standard model [4] has been in the study of rare processes. Here we will investigate whether with sufficiently high-intensity they may lead to competitive measurements of standard model parameters, specifically the electroweak mixing angle.

2. Future Perspectives of Neutrino Physics

The development of future neutrino facilities is driven by the study of neutrino masses and mix-

ings, and will happen in three stages. In the first phase various facilities will produce conventional ν beams from the decay of a secondary meson beam (producing typically $\sim 10^{18}$ ν /year). Examples of such facilities (now under construction or just commissioned) are MINOS and NO ν A, the CERN/Gran Sasso beam, and T2K. In the second stage, planned for the beginning of the next decade, “superbeams”, i.e. conventional beams but with intensities about hundred times higher, should be constructed, exploiting very high-intensity, and relatively low energy primary proton beams. Examples of such facilities are the second phase of T2K, exploiting a 50 GeV and 7 MW proton synchrotron at JParc, and a possible high-energy superbeam at CERN exploiting a 3.5 GeV, 4–5 MW superconducting proton linac (SPL). In the third phase, starting perhaps towards the end of the next decade, neutrinos from decays of a *primary* beam are planned. Two possible kinds of primary beams are envisaged: either a neutrino factory, i.e. relatively high-energy (tens of GeV) muon beam, or a β -beam, i.e. relatively low-energy (few GeV) radioactive nuclei. The advantage of using a primary beam are higher intensity and a better control on the neutrino energy spectrum. The β beam has the further advantage of giving a pure beam of electronic ν or $\bar{\nu}$, with essentially no contamination from ν_μ or wrong-sign neutrinos. The neutrino factory gives a beam which is exactly 50% ν_μ and $\bar{\nu}_e$.

3. The Weinberg Angle from Neutrino-Nucleon Elastic Scattering

Because neutrinos only couple to weak interactions, they are an ideal probe of electroweak parameters, specifically of the electroweak mixing angle (Weinberg angle) which controls the relative strength of neutral (NC) and charged current (CC) couplings. Neutrino-electron elastic scattering offers an ideally clean setting for this measurement, which is competitive at a high energy neutrino factory [3], but (because the cross section grows linearly with the energy) at a low-energy facility very high intensities are required [6]. A measurement of the Weinberg angle can be obtained from the CC/NC deep-inelastic scattering ratio: this measurement at present is almost competitive, but marred by the uncertainty related to parton distributions [7]. It would certainly be competitive at a neutrino factory [3].

As the energy is lowered, the relative (quasi)elastic contribution to the total cross section grows, and at an energy $E \sim M_N$ the elastic and inelastic contribution are of comparable size (see Fig. 1). At this energy, at which perturbative treatment of inelastic contribution breaks down anyway, the relative elastic contribution is sizable, while total cross section is still reasonably large. This energy is relevant for future facilities, such as JPARC, a low-energy β beam or the SPL superbeam, and it is natural to ask whether elastic or quasielastic scattering can be used for competitive measurements of Weinberg angle.

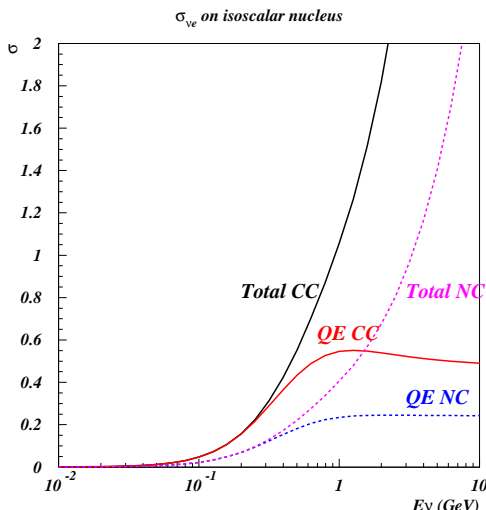


Figure 1. ν -nucleon cross sections vs. energy.

The answer is not obvious, because (quasi)-elastic cross sections depend on eight independent form factors [9]: two pairs of electric and magnetic form factors for proton and neutron targets, a pair of strange electric and magnetic form factors (the same for protons and neutrons) and a pair of axial isotriplet and strange form factors (the same for protons and neutrons, up to signs). The question is then whether the uncertainty in the form factors knowledge spoils the extraction of $\sin^2 \theta_W$ from these cross sections.

4. Results

4.1. Physical observables

The simplest answer to the above question is obtained by a counting of the relevant physical observables. With proton and neutron (from deuterium or other nuclei) targets and ν and $\bar{\nu}$ beams, one can measure four independent NC and two independent CC cross sections. They depend on eight form factors and the Weinberg angle. Hence, at least three form factors have to be input to the analysis. It is convenient to input the electric form factors, whose forward value is fixed by charge.

Assuming a flux $\Phi_\nu \sim \Phi_{\bar{\nu}} \sim 10^{11}/(m^2 yr)$ with energy $E_\nu \sim E_{\bar{\nu}} \approx 5$ GeV one gets $\sim 10^5$ elastic CC events and $\sim 10^4$ NC events with either beam or target after one year of running with each beam. This flux and energy are typical e.g. of a low-energy β -beam, with a detector located at a distance of ~ 100 Km. Assuming that the five independent form factors and the Weinberg angle are determined in each angular bin this leads to a statistical error $\Delta \sin^2 \theta_w \sim 10^{-3}$ [5].

The further theoretical error due to the electric form factor is negligible. It is important to observe that these form factors must be input if one wishes to extract all the other form factors and $\sin^2 \theta_w$. However, the cross section can actually be measured in a large number of angular (or y) bins (e.g. several dozens). One may thus choose to parametrize the form factors and fit these parameters as well as $\sin^2 \theta_w$. Clearly, with, say, 20 bins and several cross sections even with a very general parametrization all form factors can be determined together with the Wein-

berg angle. This suggests that a more detailed analysis is worthwhile.

4.2. Experimental constraints

The main experimental constraint is the possibility to detect CC and NC events with a neutrino beam energy between one and a few GeV. This rules out water Cherenkov detectors, because the Cherenkov threshold $\frac{p}{E} > 0.75$ for the recoiling proton implies that only protons with recoil momentum $p > 1.1$ GeV can be detected, which removes most of the cross section. A more promising alternative is a liquid Ar TPC [10]. In this case, the only constraint is that the recoiling proton leaves a sufficiently long track so that it is not confused with nucleon motion due to nuclear effects. This gives a constraint on the proton energy $E - m \sim 50$ MeV i.e. $p \gtrsim 300$ MeV. With a beam energy of the order of 1 GeV, about 75% of the scattering events survives this kinematic cut. However, recoiling neutrons cannot be detected. This implies that neutron neutral current (NC) events are essentially lost and one is left with only four independent cross sections.

In order to maximize the flux, one may envisage the option of having a near detector, located at a few hundreds of meters from the source, thereby obtaining fluxes by many orders of magnitude larger than those at the far detector used for oscillations studies. However, in a realistic analysis one should keep into account that an Argon TPC might have difficulties in handling interaction rates much larger than a few events per spill. This would put a bound on the maximum flux.

4.3. Quantitative analysis

In order to get a more quantitative estimate of the accuracy one can reach in the Weinberg angle determination, we have generated scattering events assuming an incoming flux $\Phi_\nu \simeq 10^{16}/(m^2 yr)$, $\Phi_{\bar{\nu}} \simeq 5 \times 10^{14}/(m^2 yr)$, with fixed energy $E = 1$ GeV. These parameters are typical e.g. of T2K (first phase) with a near detector at about 300 m from the source. In the present analysis we have considered the case of a liquid Argon detector with a mass of 10 Ktons. An increase in the detector mass would correspond to a reduction in the fit uncertainty that can

be easily obtained by standard statistical analysis. We have assumed $\sin^2 \theta_w = 0.2312$ and all the nucleon form factors as given in ref. [12] and in ref. [8,9] for the axial and strange form factors; in particular for the strange magnetic form factor we used $G_M^S(Q^2) = \frac{F_1^S Q^2 + F_2^S(0)}{(1+\tau)\left(1+\frac{Q^2}{M_V^2}\right)^2}$,

with $Q^2 = -(k - k')^2$ the neutrino momentum transfer, $\tau = Q^2/(4M_N^2)$, M_N nucleon mass, $M_V = 0.843$ GeV/c² and $F_1^S = 0.49$.

We have then performed a fit to the events thus generated, leaving as free parameters $\sin^2 \theta_w$ and the forward value of the strange magnetic form factor $G_M^S(0)$. We have then repeated this fit by varying the value of the forward strange axial form factor $G_A^S(0)$, considering one σ variation around its central value ($G_A^S(0) = -0.13 \pm 0.09$). These are the only forward form factors which are affected by a significant uncertainty. Other form factor parameters have a more moderate impact. We get $\sin^2 \theta_w = 0.2309 \pm 0.0019(\text{stat}) \pm 0.0024(\text{syst})$, where the systematic error is due to the variation of the strange axial form factor within the range indicated. Clearly, a more detailed analysis [11] would require either fitting of all form factors, or varying some of their parameters within errors. In such an analysis we will also introduce a study of the systematical uncertainty related to the choice of the form factor parametrization. However, on the basis of this first estimates, we conclude that a determination of $\sin^2 \theta_w$ with an uncertainty of a few percent is not unreasonable.

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